Performance of BPSK Subcarrier Intensity Modulation Free-Space Optical Communications using a Log-normal Atmospheric Turbulence Model

X. Tang, S. Rajbhandari; W. O. Popoola, Z. Ghassemlooy,
Optical Communications Research Group
School of Computing, Engineering & Information Sciences
Northumbria University
Newcastle, UK
xuan.tang@unn.ac.uk

S. S. Muhammad
National University of Computer and Emerging Sciences (FAST-NU)
Lahore, Pakistan
sm.sajid@nu.edu.pk

E. Leitgeb
Institute of Broadband Communications
Graz University of Technology
A-8010 Graz, Inffeldg. 12
Tel.: ++43-316-873-7442

G. Kandus
Department of Communication Systems
Jožef Stefan Institute, Jamova 39
Ljubljana, Slovenia
gorazd.kandus@ijs.si

Abstract— **In this paper, we present simulation results for the bit error rate (BER) performance and the fading penalty of a BPSK - subcarrier intensity modulation (BPSK-SIM) free-space optical (FSO) communication link in a log-normal atmospheric turbulence model. The results obtained are based on the Monte-Carlo simulation. Multiple subcarrier modulation schemes offer increased system throughput and require no knowledge of the channel fading in deciding what symbol has been received. In an atmospheric channel with a fading strength σ_l^2 of 0.1 obtaining a BER of 10^{-6} using a 2-subcarrier system will require a signal-to-noise (SNR) of 23.1 dB. The required SNR increases with the fading strength and at a BER of 10^{-9} the fading penalty due to the atmospheric turbulence is ~ 41 dB for $\sigma_l^2 = 0.9$. The comparative studies of the OOK and BPSK-SIM schemes showed that for similar electrical SNR, BPSK-SIM offered improved performance across all range of turbulence variance.**

Keywords – subcarrier intensity modulation, BPSK, turbulence, log-normal channel model.

I. Introduction

Transmission by light (laser) over free space has received a significant attention as a complementary technology to the radio frequency (RF) based techniques by a number of researchers [1, 2]. The ever increasing demand for higher bandwidth coupled with last mile bottleneck imposed by the RF based systems have forced service providers to look for alternative systems in certain dedicated applications. FSO with availability of unregulated bandwidth in excess of THz is seen as the ultimate solution for overcoming the access network bottleneck. In addition FSO links offer a number of advantages including a secure transmission, smaller and more compact transceiver modules, a low development and installation cost and immunity to the electromagnetic interference [3].

The reliability of an FSO communication system is greatly influenced by the atmospheric conditions. The beam scattering caused by fog and haze can significantly reduced the received optical signal level. Heavy fog causes attenuation greater than 300 dB/km, thus limits the link length to < 100m. Rain and snow affect mainly the radio and microwave frequencies but their effects are not deleterious for FSO systems. However FSO can encounter significant losses in a clear sky condition due to inhomogeneities in temperature and pressure [4, 5]. Scintillation severely limits the reliability of FSO links as it deteriorates the signal intensity at the receiver and can even result in complete loss of communication links [2]. The effect of scintillation is more severe for small aperture receivers [4, 6]. However, increasing the detector collection aperture is not the best solution as there is an optimum aperture size to minimize the scintillation level. Making the collector aperture diameter much larger than the minimum aperture diameter results in very little SNR improvement [6].

The appropriate selection of the modulation technique is vital to circumvent turbulence induced fading. Though the on-off keying (OOK) scheme is the simplest and extensively used modulation technique [7, 8], it does not offer immunity to the turbulence induced fading [2, 5, 8]. The non-predictive behavior of turbulence level gives rise to the random fluctuation of the optical intensity level at the receiver. This implies that the OOK will require an adaptive thresholding scheme to perform optimally. This adaptive thresholding is complex to implement and practically not suitable [5, 9]. Since

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scintillation affects the optical intensity level, it is a reasonable approach to use modulation techniques that carries the information in the phase or the frequency of the carrier signal. The phase shift keying (PSK) based subcarrier intensity modulation requires no adaptive thresholding scheme, thereby offering superior performance compared to the OOK in the presence of the atmospheric turbulence induced fading channels [7]. In this work BPSK-subcarrier intensity modulation (BPSK-SIM) is investigated, where SIM is used to increase the system capacity by modulating multiple sources at different subcarriers. However, the penalty paid is the higher SNR to attain a desired BER performance. Hence multiple SIM is the preferred choice when increased capacity is more important than the power requirement [10].

The rest of the paper is arranged as follows: the lognormal turbulence model for FSO is introduced in Section II, followed by the detailed description of the proposed BPSK-SIM system in Section III. The simulation results for the BER for the BPSK-SIM scheme in turbulent atmospheric channel is presented in Section IV. The simulation results are verified using a theoretical BER performance and fading penalty is calculated for a number of desired BERs. Finally, conclusions are presented in Section V.

II. LOGNORMAL TURBULENCE MODEL

The atmospheric turbulence impairs the performance of an FSO link by causing the received optical signal to vary randomly thus giving rise to signal fading. The fading strength depends on the link length, the wavelength of the optical radiation and the refractive index structure parameter C_n^2 of the channel. The log-normal distribution is generally used to model the fading associated with the weak atmospheric turbulence regime [2, 8, 11]. This model is mathematically tractable and it is characterised by the Ryotov variance σ_l^2. The turbulence induced fading is termed weak when $\sigma_l^2 < 1.2$ and this defines the limit of validity of the log-normal model [8]. Beyond the weak turbulence regime, other models such as the gamma-gamma [11] and the negative exponential [8] will have to be considered. The Ryotov variance σ_l^2 can be calculated as [4]:

$$\sigma_l^2 = 1.23 C_n^2 \left(\sqrt[6]{k^7 L^{11}}\right); \tag{1}$$

where L is the propagation distance and k is the wave number.

The log-normal models assumes the log intensity l of the laser light traversing the turbulent atmosphere to be normally distributed with a mean value of $-\sigma_l^2/2$. Thus, the probability density function of the received irradiance is given by [11, 12]:

$$p_I = \frac{1}{\sqrt{2\pi}\sigma_l}\frac{1}{I}\exp\left\{-\frac{(\ln(I/I_0)+\sigma_l^2/2)^2}{2\sigma_l^2}\right\} \qquad I \geq 0; \tag{2}$$

where I represents the irradiance at the receiver and I_0 is the signal irradiance without scintillation.

III. PROPOSED BPSK-SIM SYSTEM

Figure 1 shows the block diagram of the BPSK-SIM system with two subcarriers, if necessary more subcarriers can be used for increased throughput. Using BPSK, the input data $\{d_1, d_2\}$ are modulated onto the RF subcarriers whose amplitudes, frequencies and phases are $\{a_{c1}, a_{c2}\}$, $\{\omega_{c1}, \omega_{c2}\}$ and $\{\varphi_{c1}, \varphi_{c2}\}$, respectively. In Fig. 1 $g(t)$ represents the pulse shaping function. The combination of the two RF subcarrier signals is then used to modulate the intensity of the optical source. Prior to this, a D.C. signal b_0 is added to the composite RF signal, to ensure that the optical source is appropriately biased at the centre of its linear dynamic range so as to accommodate the full swing of the sinusoidal subcarrier signal. In the atmospheric channel, turbulence effect modeled using the log-normal causes the intensity of the transmitted optical signal to fade. At the receiver, the composite SIM signal superimposed on the envelope of the incoming optical signal is recovered via the direct detection (DD) scheme. Electrical bandpass filters are used to capture individual subcarriers $i_{si}(t)$ followed by the standard RF coherent detector to recovers the transmitted data sequence { $\hat{d}_1, \hat{d}_2$ }. The system noise (thermal and shot) is modeled as an additive white Gaussian (AWGN) and no intersysmbol interference is considered since the link under consideration is a direct line of sight with no multipath propagation.

The received photocurrent can therefore be modeled as follow:

$$i(t) = RI[1 + \xi m(t)] + n(t); \tag{3}$$

where I represents the optical irradiance, R is the photodetector responsity and $n(t) \sim N(0, \sigma^2)$ represents

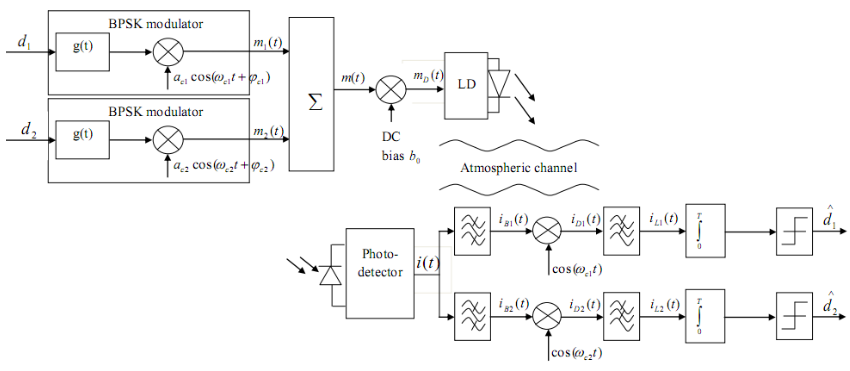

Figure 1. The block diagram of subcarrier BPSK system.

AWGN with $\sigma^2 = \sigma^2_{Thermal} + \sigma^2_{Bg}$. ξ is the optical modulation index and to keep the optical source within its dynamic range the condition $|\xi m(t)| \le 1$ must always hold.

IV. SIMULATION RESULTS DISCUSSION

The system described above is simulated using the Monte-Carlo approach in Matlab. In the simulation, the pulse shaping function is assumed to be rectangular and the amplitude $\{a_{c1}, a_{c2}\}$ of each subcarrier signal is obtained from 1/2ξ. The simulation parameters are given in Table I.

TABLE I. SIMULATION PARAMETERS

Parameters		Values
Data rate R_b		1 Mbps
1st Carrier frequency		4 MHz
2nd Carrier frequency		8 MHz
Sampling frequency		20 MHz
Laser wavelength λ		850 nm
Number of subcarriers N		2
PIN photodetector reponsivity R		1
Optical modulation index ξ		1
Butterworth Bandpass filter	Order	6
	Centre frequency	4 MHz
	Bandwidth	2 MHz
	Order	6
	Centre frequency	8 MHz
	Bandwidth	2 MHz
Butterworth Lowpass filter	Order	6
	Bandwidth	1 MHz
Lognormal variance σ_l^2		$0.1 \le \sigma_l^2 \le 0.9$ W

In order to show the effect of scintillation and noise on the system performance, we will be looking at the BER metric and fading penalty under different channel conditions. It should however be mentioned that since both subcarrier channels are BPSK modulated, their error performance will be similar and we will therefore be presenting results for one of them only. By adopting the approach given in [13], the theoretical unconditional BER per subcarrier channel is obtained as:

$$P_e = \int_0^\infty P_{ec} p(I) dI \\ = \int_0^\infty Q\left(\sqrt{\gamma(I)}\right) \frac{1}{I\sqrt{2\pi\sigma_l^2}} \exp\left\{-\frac{\left[\ln I/I_0 + \sigma_l^2/2\right]^2}{2\sigma_l^2}\right\} dI \quad ; \qquad (4)$$

where $\gamma(I)$ represents the SNR at the input of the coherent demodulator.

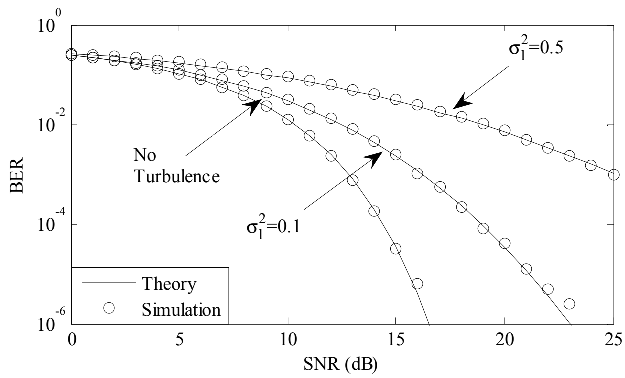

Figure 2: The theoritical and simuled BER against the SNR in a weak atmospheric turbulence FSO channel with a scintillation $\sigma_l^2 = \{0, 0.1, 0.5\}$

Figure 2 illustrates the predicted and calculated (using (4)) BERs performance against the SNR in a weak atmospheric turbulence channel with $\sigma_l^2 = \{0, 0.1, 0.5\}$. The simulated and theoretical curves match very closely for all scintillation levels, thus confirming the validity of the simulation. It can clearly be observed that the SNR required to achieve a desired BER increases with the atmospheric turbulence level. To achieve a BER of 10^{-3}, an additional ~3.4 dB of SNR is required compared to the ideal channel (without turbulence) when $\sigma_l^2 = 0.1$. However, the SNR differences between the ideal channel and $\sigma_l^2 = 0.5$ increases to ~ 12.2 dB. Further increment in the SNR requirement to achieve a BER of 10^{-6} is observed with increasing scintillation levels.

Further insignt into the effect of turbulance can be obtained by ploting the fading varience against the fading penalty, see Figure 3. The fading penalty represents the increment in SNR to acheive a desired BER in a tubulance channel compared to the ideal channel. The figure demonstrates that the fading penalty increases with the turbulance variance irespective of the BER. For the same turbulence level, fading penalty is higher for lower BER. For example, when the turbulence variance is 0.5 the fading penalty are ~ 12.2 dB , 21.1 dB and 27.7 dB for BER of 10^{-3}, 10^{-6} and 10^{-9}, respectively. The

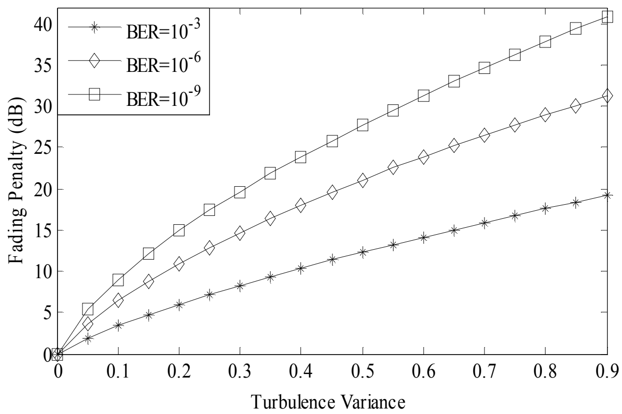

Figure 3: The fading penalty againt the log intensity for multiple subcarriers FSO system in weak atmospheric turbulence under different BER condition.

fading penalty can be as high as ~ 41 dB when the turbulence variance is 0.9, thus demonstrating the vulnerability of the system under high turbulance conditions.

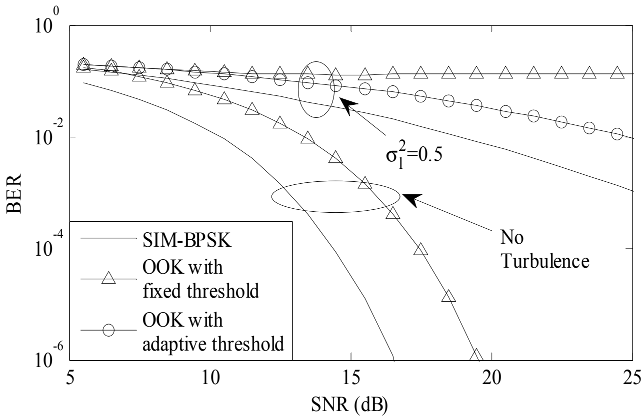

Figure 4: The BER performance of OOK and SIM-BPSK schemes against the SNR under turbulence variances of 0 and 0.5.

The comparative studies of the BER perfromances of OOK and SIM-BPSK under a weak turbulance atmospheric condition is carried out and are demonstrated in Figure 4. A threshold level of half of the mean of the received intensity is selected for the fixed threshold level in the OOK system. Though the threshold level is optimum for OOK in channel without turbulance, it is clearly demonstrated that a fixed threshold value is non-ideal in the presence of turbulance. The fixed threshold can not optimize the performance of OOK scheme over weak turbulence, while the adative threshold can optimize the performance by reducing the BER. Based on similar electrical SNR values, the penalty due to the turbulance is much higher for the optimum OOK scheme compared to the BPSK-SIM even in weak turbulance channel. The fading penalty at the turbulence variance of 0.5 is ~ 21.1 dB for BPSK-SIM to achieve a BER of 10^{-6}. However the fading penalty at the variance level is much higher even for OOK with adaptive threshold indicating superior performance of the BPSK-SIM in fading channels. The difference in the performance is attributable to the difference in the methods of representing information signals on the optical carrier.The received irradiance of OOK represents digital information and any fluctuation in the irradiance increases the error probability. However, information is transmitted by modulating the subcarrier phase in BPSK, which is less affected by the irradiance fluctuation.

v. CONCLUSIONS

This paper illustrated the BER performance and fading penalty of a FSO communication link through the weak atmospheric turbulence channel for the BPSK-SIM scheme using the Monte-Carlo simulations. The results illustrated that fading penalty increases with the turbulence level. The fading penalty of ~ 21.1 dB is observed at a turbulence variance of 0.5 at a desired BER of 10^{-6}, however a much higher penalty of ~ 41dB is incurred at a turbulence variance of 0.9. The comparative studies of the OOK and BPSK-SIM base on similar electrical SNR schemes showed that BPSK-SIM offers improved performance for all range of turbulence variance.

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